

Photonic crystal fibers and fiber lasers (Invited)

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Photonic crystal fibers and fiber lasers have been two of the most rapidly evolving areas of optics and photonics over the past few years. Recent developments in the field of photonic crystal fibers are enabling new ways to generate, transform, and deliver light, and have significant implications for fiber laser design and applications. We review the ways in which photonic crystal fibers are affecting and may further affect the development and deployment of fiber laser technology. © 2007 Optical Society of America

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1. INTRODUCTION

The past few years have seen massive progress in the performance of fiber lasers (see other papers in this special edition). Apparently “fundamental” limits to their ultimate performance have evaporated as output powers have increased and pulse lengths and linewidths decreased to the point where they now present a serious challenge to many types of conventional laser systems. Over the same period, and independently, optical fibers have themselves been undergoing something of a revolution—conventional fibers have not been superseded, but a host of new concepts in fiber-optic design have been identified. These have served to greatly broaden the range of performance that can be expected from a fiber. The change in thinking about fibers began in the early 1990s [1], but accelerated radically following a few key breakthroughs in the closing years of the 20th century [2,3]. Photonic crystal fibers (PCFs) are waveguiding optical fibers in which the waveguiding is due to complex microstructuring of the fiber cross section [4,5]. Most commonly, the microstructure is an array of air holes running down the fiber length. The first simple PCF laser was reported in 2000 [6]. Since then, a large number of ways of using PCFs both in and with lasers have been reported, as described schematically in Fig. 1. It is now appropriate to review the recent progress in the new forms of optical fiber, in order to establish the implications for future high-performance fiber laser systems.

2. PHOTONIC CRYSTAL AND MICROSTRUCTURED FIBERS

The new family of optical fibers that has been developed over the past few years has arisen following the realization that naturally occurring (and synthetically produced) homogeneous materials can be structured on the micro-scale to produce completely new optical materials, with properties not otherwise attainable. In large part, this thinking arose from a widespread interest in photonic bandgap materials in the early 1990s. Indeed the primary

objective of the work into microstructured optical fibers in the early 1990s was to form a photonic bandgap fiber [1]. Such photonic bandgap fibers now form a subset of the new family of fibers that rely on regular microstructuring to create optical effects. In this paper, we will loosely group these together as PCFs. Within this classification, we include the fibers also referred to as microstructured fibers and holey fibers.

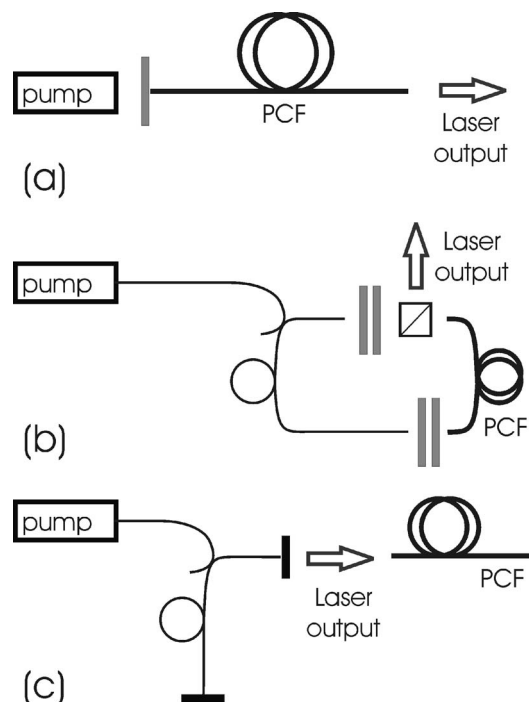


Fig. 1. Relevance of PCFs for fiber lasers. PCFs can be used as a gain medium in lasers and amplifiers [as shown in (a)], to take advantage of the large-core-area single-mode performance or the high-NA cladding. They can be incorporated as linear or nonlinear intracavity elements in fiber laser cavities (b), for example, to manage GVD or affect the gain spectrum, or they can be used to manipulate the spectral and temporal properties of the laser beams (for example, pulse delivery, pulse compression, wavelength conversion, and supercontinuum generation).

In PCFs, the microstructured or photonic crystal material forms the fiber cladding. The core in which the light propagates is formed by omitting one or more periods of the photonic crystal (leaving an air core) or by filling in one or more air holes (forming a solid core) as illustrated in Fig. 2. Although PCFs have been formed from different glasses, we focus our attention in this paper mainly on those formed from silica and doped silica, and containing voids or air holes, as these are most compatible with the vast bulk of fiber lasers.

The new fibers fall into two broad groups. In one, the effective refractive index of the composite material is reduced below the refractive index of the higher-index material, which makes it possible to trap light in a core formed from the higher-index material by a form of total internal reflection. For example, an air-silica microstructured material has an effective refractive index below that of pure silica. As a result, light propagating in a pure silica region (a solid core) can be totally internally reflected from a photonic crystal region (the cladding). Figures 1(a) and 1(b) show two examples of such structures. In the second group of fibers, a regular array of high-index scatterers causes a bandgap to appear in the transmission characteristics of the composite material. By nature, the bandgap corresponds to values of modal index that are below the effective index of the composite material, and can even be below the refractive index of the lower-index material. As a result, in a bandgap fiber, the core can be formed from the lower-index material, which could be solid glass [Fig. 1(c)] or, in the case of an air-glass photonic crystal, a large air hole [Fig. 1(d)]. The characteristics of these two types of fibers are very different, as are, for the most part, their potential application to fiber lasers. In the following sections, we briefly review

the most relevant properties of the two classes of fiber as they relate to fiber lasers. We will then describe the different applications that have been reported, illustrating with relevant examples from the literature. At the end of the paper, we will describe some recent developments.

3. EFFECTIVE REFRACTIVE INDEX FIBERS

Fibers that guide using the “effective refractive index” effect are in many ways similar to conventional fibers. Once the effective refractive index of the composite microstructured cladding material has been evaluated at a particular frequency [7,8], the optical response of the fibers can be analyzed in a way very similar to that used for conventional fiber designs [9,10]. However, the results are different for two reasons. First, the range of effective indices attainable is far greater than that which can be obtained using conventional fiber technology. Second, the effective refractive index of the composite material is far more dispersive than the refractive index of bulk silica. As a result of these two differences, effective-index fibers offer tremendous control over the group-velocity dispersion (GVD) of the guided mode, large-mode areas, ultrahigh nonlinearity and numerical apertures approaching unity.

A. Group-Velocity Dispersion and Nonlinearity

Because these fibers have solid cores, the starting point for their GVD is the GVD of bulk silica. Although the GVD of the fibers cannot be computed by adding together the constituent GVD curves arising from different mechanisms, it is nonetheless instructive to consider the relative magnitudes of the GVD arising from the material and waveguide dispersions. Figure 3(a) shows the GVD of bulk silica, computed using the data in Ref. [11]. The form of this curve is well known: the GVD is normal (negative D) for wavelengths below 1300 nm, and anomalous at longer wavelengths. Because this behavior has its origin in the existence of the electronic and infrared absorption bands, curves for different glasses generally have a similar form, although scaled differently on both axes. Representative values of the material GVD for fused silica are $D=30$ ps/nm km at approximately 1550 nm wavelength (anomalous dispersion), and $D=-100$ ps/nm km at 800 nm wavelength (normal dispersion). To compare the material GVD with that arising from the waveguiding effects, we have computed the GVD of a fine strand of glass surrounded by air. This structure is a good approximation to a small-core PCF [12]. In performing the computations, we have assumed a single constant value of the material refractive index (assumed $n=1.5$), and so the variation shown arises only because of the variation in the relative core size with wavelength. This “waveguide” GVD is plotted as a function of the core diameter over the wavelength. The waveguide GVD is low for large cores, becoming strongly anomalous as the core size decreases. When the core diameter is comparable with the wavelength, the GVD becomes strongly normal for yet smaller cores, before returning to zero as the core size approaches zero. This strong waveguide dispersion arises from a strongly guided mode and a high refractive index contrast, and so implies small core dimensions for a single-mode fiber. As a

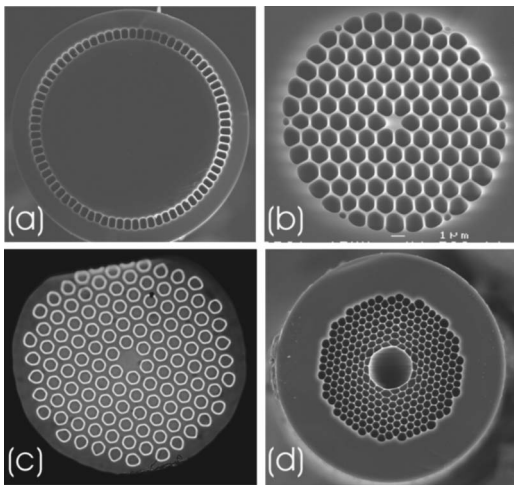


Fig. 2. Scanning electron micrographs of different forms of PCF. (a) shows a large core supported by fine strands of glass, to form a high-NA multimode structure as required for cladding pumping a fiber laser. (b) is a single-moded or few-moded fiber with unusual dispersion and a high nonlinear response, useful for dispersion management (for example, in a mode-locked fiber laser) and nonlinear processing. (c) and (d) are different forms of photonic bandgap fiber, in which light can be guided only in narrow spectral ranges. (c) shows an all-solid bandgap fiber, with a pure silica core surrounded by a matrix of raised-index rings. In (d), the core is hollow, greatly reducing the nonlinear response of the fiber.

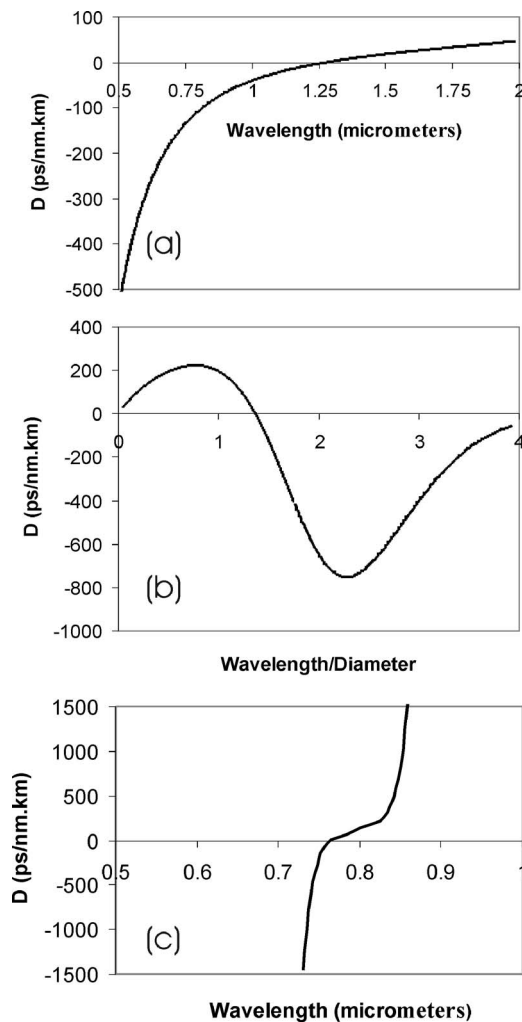


Fig. 3. GVD in PCFs. (a) The GVD D of bulk silica. (b) GVD D due purely to waveguide dispersion for a fiber of diameter $2\text{ }\mu\text{m}$, refractive index $n=1.5$ and surrounded by air ($n=1$). The waveguide GVD is comparable to the material GVD shown in (a) over a wide range of wavelengths. The structure is a good approximation to a PCF with a high air-filling-fraction cladding. The variation of modal index from which this curve is derived is shown as an inset. (c) Measured GVD in a hollow-core photonic bandgap fiber.

result, many of the fibers that have useful dispersion characteristics will unavoidably also have a high nonlinear response, by virtue of their small-core areas.

Conventional optical fibers and low-index-contrast PCFs also exhibit waveguide GVD with a similar dependence, but the magnitude is typically approximately 100 times smaller. As a result, in a conventional fiber waveguide dispersion can only make a modest contribution to the overall dispersion, and the impact is limited to those spectral regions where the material GVD is small.

B. High Numerical Apertures

The effective index of a PCF cladding can be evaluated by analyzing the electromagnetic modes of the cladding (neglecting the effects of the outer boundaries). In general, we need to evaluate the mode that has the highest propagation constant, as this will define the effective index as relevant for total internal reflection. Exactly how the

structure can best be analyzed depends on the details of the structure of interest. For fibers in which the cladding is a two-dimensional array of air holes in a background matrix, one can model the lowest-order mode by considering a unit cell of the cladding, with appropriate boundary conditions [7]. If the holes are much larger, so that the cladding appears more like a pattern of silica waveguides [8], it may be more appropriate to analyze the propagation constants of these strands as planar waveguides. As an alternative, the properties of the cladding can be analyzed by one of a number of numerical methods. However, if a high-index contrast between the core and cladding and thus a low cladding index is required, no modeling is required to understand that the effective index of the modes of the silica strands in the cladding will not drop significantly below the index of the high-index material until the width of the silica strands is less than the wavelength of the light of interest [8]. Thus a high NA requires a network of very fine struts of silica as a cladding, as shown in Fig. 2(a).

C. Large-Mode Areas

On the other hand, if one is concerned to try and form a single-mode guide, the dispersion of the cladding effective index makes it possible to design a very large core [13] that remains intrinsically single mode. This is possible because with increasing scale of the structure, the effective-index contrast between core and photonic crystal cladding becomes very low, but in a manner that is completely determined by the structure rather than by using vanishingly low levels of dopant. For large air holes, the fiber core behaves increasingly like a strand of silica completely surrounded by air, guiding many modes if the core size is large. However, as the air hole size is reduced (relative to the interhole spacing and core size) higher-order modes are cut off, independent of the wavelength or the actual value of the core size. In certain cases, the fiber will always only guide just a single mode, independent of the size of the core [7,14]. This concept has since been extended in various ways to establish a number of useful fiber designs [15,16]: however, the effects of bend loss are inescapable and form a firm practical barrier to making arbitrarily large low-loss single-mode cores in a flexible geometry.

4. PHOTONIC BANDGAP FIBERS

Photonic bandgap fibers are profoundly different from standard fibers. They guide light only in one or more discrete spectral bands corresponding to the photonic bandgaps, and the guided modes have effective index less than that of the cladding. Indeed, the guided mode index can be less than unity, enabling propagation in an air core. The implications of this are broad: the performance of the fiber is no longer intrinsically limited by the material properties of bulk silica. As a result, one can anticipate the propagation of high optical powers (either cw or pulsed) with greatly reduced nonlinear response and increased damage threshold. As one might anticipate in such an unusual waveguide, the dispersion of the guided modes is also completely different from those in standard fibers.

A. Group-Velocity Dispersion

Near the center of a guiding band, the dispersion of the mode is low. As one moves toward the edges of the bandgap, the mode spreads out as the confinement drops. The GVD is then normal as one moves out of the bandgap toward shorter wavelengths and anomalous as one moves toward longer wavelengths. The GVD passes through zero somewhere within the bandgap, depending on the relative contributions of the waveguide dispersion (which is always anomalous in bandgap fibers in which the core is inevitably larger than the wavelength) and possible material dispersion (in the case where the core is solid or liquid), which could be normal or anomalous, depending on the material and the wavelength. The GVD of a hollow-core photonic bandgap fiber [17] over the low-loss transmission band is shown in Fig. 3(c). In a solid PBG fiber, a similar curve is repeated in each of the transmission bands [18].

B. Nonlinearity and Damage Threshold

Hollow-core fibers were expected to and have been shown to have greatly reduced nonlinear response compared with conventional fibers. The reduced nonlinear response arises because the guided light is strongly peaked in the air- (or other gas-) filled core, and the nonlinear response of gases is generally low (at least, far from resonance). Ouzounov *et al.* [19] showed that the nonlinear coefficient of hollow-core PCFs was approximately 3 orders of magnitude less than that of standard fibers and was effectively due solely to the contribution from the gas in the core. Working at a shorter wavelength (and with a slightly different fiber design) Bouwmans *et al.* [17] found that the contribution from the silica surrounding the core could not be neglected, but made a significant contribution to the overall nonlinear response. The dispersive nature of the fibers means that the relative contributions from the gas and the glass will vary across the bandgap, [20] but in a well-designed fiber the assumption that the nonlinear response will be due only to the gas appears to be a reasonable starting point.

Hollow-core fibers were also predicted to have greatly increased damage thresholds when compared with standard fibers, but this has yet to be realized for delivery of external laser pulses. Superior performance to standard fibers has been reported, but not anything like as much as hoped. At 1064 nm, Shephard *et al.* [21] reported delivering 20 W average power of 65 ns pulses at 60 kHz repetition rate. One reason for the damage is that the coupling into hollow-core fibers is not close to 100%. Thus even a very acceptable figure for the coupling efficiency of 80% leaves some 20% of the power incident on the endface not coupled into the guided mode. This limits the ultimate power handling capacity of the fibers for delivery of pulses from external laser sources.

5. HIGH-POWER SINGLE-MODE FIBER LASERS

Several possible applications of photonic crystal or microstructured fibers have been proposed in the development of high-power fiber laser sources [Fig. 1(a)]. These rely on incorporation of rare-earth dopants directly into the PCF,

forming an active fiber. The first cladding-pumped PCF lasers [22,23] were reported shortly after the very first active PCF. Furusawa *et al.* [22] reported a structure comprising an inner and an outer photonic crystal cladding, with a single-mode core (see Fig. 4). The NA of the cladding is given as 0.3 to 0.4 or less (depending on the length), and the mode field diameter of the Yb-doped core was a modest 12.3 μm . Respectable performance as a low-power laser was reported (60% slope efficiency when cladding pumped), with 1 W output power, but at this stage, the NA of the cladding was a limiting factor.

In 2003, Limpert and colleagues [25] reported significant progress using a similar but improved fiber design. By decreasing the size of the air holes in the inner cladding, using a larger core (diameter 28 μm , MFD=21 μm), and substantially reducing the widths of the glass strands forming the outer cladding, they increased the cladding NA and the rate at which energy was absorbed by the doped core (0.6 at. % Yb ions). Due to the high level of doping, the fiber was slightly overmoded, but operated as single-mode under normal bending conditions. The NA of the inner cladding was reported as 0.55, giving a pump absorption of 9.6 dB/m at 976 nm. The 2.3 m laser emitted up to 80 W with a slope efficiency of 78%. No thermal limitations were found at that level, and the authors pro-

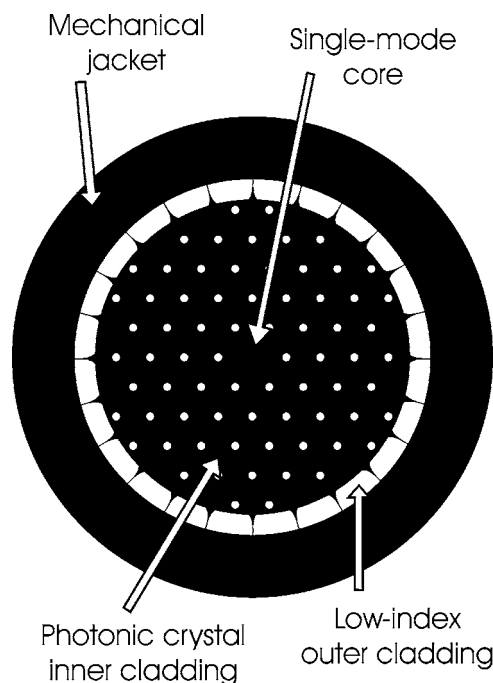


Fig. 4. Elements of a cladding-pumped PCF laser or amplifier fiber. The inner cladding is a two-dimensional photonic crystal material, with an effective index just slightly less than the refractive index of the doped silica in the core. The core is defined both by the presence of the active rare-earth elements (for example, Yb) and codopants (such as aluminum) and also by the absence of the air holes that are present in the inner cladding. In the structure illustrated, just a single air hole is missing (a "single-cell defect") but other fiber designs have been reported (Ref. [24]) using three, seven, or more missing holes. The outer cladding is a high-air-fraction layer, formed of fine strands of silica with widths of less than the optical wavelength. The entire structure is contained within a supporting silica jacket and may be covered with a further coating material.

posed that such lasers should be scalable to the kilowatt power level.

The high pump absorption reported in Ref. [25] suggested that a fruitful way to proceed might be to increase the core size to enable higher powers, while simultaneously decreasing the fiber length. Numerical studies by Mafi *et al.* [26] predicted remarkable performance for highly doped fibers with lengths of just a centimeter or two. This was first pursued experimentally using a large-core fiber with a seven-cell core [27], as an amplifier for short pulses. A mode-locked seed source supplied 10 ps pulses into a cladding-pumped PCF with a 40 μm single-mode core diameter. The pulses were amplified to an average of 48 W with a slope efficiency of 74%. The short amplifier length and large-core diameter meant that even at this level the self-phase modulation in the amplifier was modest, enabling frequency doubling with 50% conversion efficiency in a critically phase-matched bulk LBO crystal.

The idea of a short gain region with high pump absorption has been applied to a laser cavity as well. Limpert *et al.* [28] reported a 48 cm long photonic crystal “fiber”—actually, a rod of several millimeters outer diameter. By use of a large outer diameter, the authors avoid any issue of bend loss (the fiber does not bend) and make use of the very high pump absorption that is possible with a large (35 μm diameter) single-mode core and a high-NA (NA = 0.6) inner cladding. The small ratio between the inner cladding and core diameters (roughly 4:1) resulted in pump absorption of 30 dB/m at 976 nm. The laser delivered 120 W of output power with a slope efficiency of 74%, comparable to conventional fiber designs. The power extraction was an impressive 250 W/m. Li and co-workers [29,30] took this idea even further, finally demonstrating a 35 mm length fiber laser formed using phosphate glass and generating 4.7 W single-mode output power. A similar fiber was recently demonstrated [31] as a high-power (2.3 W) single-frequency fiber laser by splicing it to conventional fibers incorporating fiber Bragg gratings. The laser performance benefited from the large-mode area, not suffering from the power saturation behavior previously observed in a similar system but using a conventional doped fiber.

Brooks and Di Teodoro [32] and Di Teodoro and Brooks [33] have reported master oscillator–fiber amplifier configurations in which a double-clad Yb-doped PCF with a single-mode 40 μm diameter core was used to amplify nanosecond-scale pulses from a Q-switched microchip laser at approximately 1060 nm wavelength. The PCF was terminated using beam-expanding endcaps to reduce endface damage and enable endface polishing. The output of the PCF stage was approximately 10 W average power and over 1.5 MW peak power. In a further experiment [33], they added another stage of amplification consisting of a doped multimode fiber, which enabled peak powers of 4.5 MW, although with a degraded beam quality ($M^2=9$). A similar amplifier fiber to that in Ref. [27] has also been used in chirped-pulse amplification schemes. Röser and colleagues [34] used bulk gratings to stretch and recompress their pulses, with two stages of PCF-based amplification between the stretcher and the compressor. The final output was an impressive 131 W average power for a

pulse train at 73 MHz and 220 fs pulse length. The incident pulses of 150 fs were stretched to 120 ps before the amplification, and the amplifier fiber had sealed and angle-polished endfaces to reduce damage and parasitic lasing.

All of the work described so far has relied on the use of end pumping using high-brightness laser diodes or single-mode pump sources. An alternative approach has been demonstrated by Larsen and Vienne [35]. They have shown that it is possible to locally collapse the outer cladding of the fiber without substantially affecting the core-guided mode. Collapsing the outer cladding enables optical access to the inner cladding, so enabling direct injection of pump light. The authors placed an angle-polished multimode pump fiber in optical contact with the collapsed region, at a coupling angle of 20°. The 976 nm pump light was coupled in with 90% coupling efficiency and absorbed at 0.8 dB/m.

Control of the output polarization state is frequently of great importance for fiber laser design, for example, for efficient subsequent wavelength conversion in a nonlinear crystal, or for beam recombination. Several solutions to this problem have been reported for fiber lasers based on PCFs. Perhaps the most impressive and interesting was the work reported by Schreiber and colleagues [36], who replaced some of the air holes around the single-mode core with reduced-index boron-doped rods. These introduced stress into the single-mode core, and through careful design resulted in a large-mode-area broadband single-polarization fiber. They demonstrated the effectiveness of this in a laser configuration by showing that a high polarization extinction of greater than 15 dB was obtained at output powers up to 25 W, with a slope efficiency of 75%.

6. ULTRASHORT-PULSE LASERS

Mode-locked fiber lasers are compact, reliable, and maintenance-free sources of short optical pulses. They can be either passively or actively mode locked. The most attractive configurations are self-starting and passive, using, for example, nonlinear polarization rotation or saturable absorption as a mode-locking mechanism, but these can be harder to design so as to run stably, and are often less flexible in operation. To produce short pulses, the dispersion of the fiber has either to be very low, or to sum to zero or a low value after a round trip in the cavity. This is easy to achieve in an all-fiber configuration when Er ions are the gain medium and the operational wavelength is ~ 1550 nm, because the GVD of standard fibers is low and pliable in this wavelength range. As a result, all-fiber Er-doped mode-locked fiber lasers are widespread. By contrast, if mode-locked operation at shorter wavelengths is required, for example, using Yb³⁺ ions as the gain medium for lasing at approximately 1080 nm, all-fiber operation is conventionally challenging because all standard single-mode fibers have a significant normal dispersion at this wavelength [see Fig. 3(a)]. As a result, most mode-locked Yb fiber lasers had until recently relied on the use of bulk grating compression for anomalous dispersion, to compensate the normal dispersion of the fibers.

The first report of a mode-locked laser incorporating a PCF was in 2001 [37]. This configuration was based on active mode locking of a length of small-core Yb³⁺-doped fiber using frequency-shifted feedback. The fiber had anomalous dispersion at the laser wavelength, and the laser ran with a high slope efficiency of 75%. The output pulse length was ~ 15 ps. Shorter-pulse operation could perhaps have resulted through the use of nonlinear polarization rotation, had the birefringence of the fiber been lower. However, the very short polarization beat length in this fiber (0.3 mm, due to form birefringence) precluded the use of this effect. Lim [38] and co-workers overcame this barrier in 2002, designing a cavity using a lower-birefringence undoped PCF as a dispersive element. When mode locking was initiated using an acousto-optic modulator, it was sustained for hours after the modulator was switched off. The output pulse length was ~ 120 fs, and the laser oscillated with a single pulse in the cavity, except for a small parasitic pulse due to the fiber birefringence. The birefringence also led to a modulation in the pulse spectrum. Avdokhin *et al.* [39] demonstrated a figure-of-eight configuration based on Yb, in a completely fiber-integrated format. This required the development of methods to splice the anomalous-dispersion PCF directly to the pigtailed of their nonlinear amplifying loop mirror. They observed several features familiar from earlier work at longer wavelengths using a conventional Er-doped fiber. Lim and Wise [40] showed that a hollow-core photonic bandgap fiber could be used to control dispersion in such a laser. They subsequently demonstrated [41] an environmentally stable femtosecond laser system based on Yb-doped fiber by using a hollow-core photonic bandgap fiber that had strong birefringence to control the polarization state and anomalous dispersion to compensate for cavity dispersion. Mode locking was initiated using an acousto-optic modulator but was self-sustaining thereafter. The positively chirped output pulses of 1 nJ energy could be dechirped to 70 fs, with residual chirp attributed to the third-order dispersion of the hollow-core fiber.

Moenster and co-workers [42,43] reported mode locking of an Nd-based laser system at a similar wavelength, but using a semiconductor saturable absorber mirror as a mode-locking element. To get this laser to run reliably, the authors needed to suppress the reflections from the PCF endface. They did this by filling the holes with UV-curable resin, and then angle-polishing the fiber end back until just a short length of resin-filled fiber remained. The laser then ran continuously mode locked, with no evidence of Q switching. However, due to the residual intracavity dispersion, the output pulse duration of 26 ps was strongly chirped. Lim *et al.* [41] believe that with the incorporation of such a saturable absorber element into a cavity similar to that in Ref. [41] a stable self-starting Yb-based femtosecond system will be achieved.

7. PULSE MANIPULATION

A lot of further work in the area of ultrashort pulses is focusing on increasing the power of fiber-based femtosecond systems [44]. Extension to higher powers typically involves the use of chirped-pulse amplification: dispersing the pulse is usually relatively easy, as the input pulse en-

ergies are typically low. The pulse amplification can then be done using a single-mode cladding-pumped doped fiber, as described above. Recompressing the amplified pulse train is the challenging part, because when compressed, the peak powers will induce substantial and detrimental nonlinear effects. The very low nonlinear response of hollow-core fiber, coupled with anomalous dispersion over much of its low-loss transmission window, suggests that it might be a useful way to recompress amplified pulses. Such systems were reported by Limpert *et al.* [45] and by de Matos *et al.* [46]. Unlike solid-core PCFs, the dispersive properties of hollow-core fibers vary little when used in different wavelength bands, because the material dispersion of air can be neglected compared with the other factors. As a result, hollow-core-based compression of chirped pulses has been demonstrated both at approximately 1040 and 1520 nm wavelength. At 1040 nm [45], a standard chirped-pulse-amplifier configuration was demonstrated with a PCF fiber amplifier and a hollow-core compression stage. The recompressed output consisted of 100 fs pulses at an average power of 6 W and a repetition rate of 73 MHz, corresponding to a pulse energy of 82 nJ. In a standard fiber, such pulses would produce a massive supercontinuum after propagating just a few millimeters. De Matos *et al.* [46,47] also reported nonlinear propagation of 40 ps pulses produced by modulating a telecom diode (1548 nm wavelength) were amplified in Er-doped fiber amplifiers and then launched into several kilometers of conventional optical fiber with normal dispersion. Self-phase modulation coupled with normal dispersion during the propagation led to both spectral and temporal broadening. They also reported [47] how the pulses were then further amplified before being recompressed in a hollow-core fiber. The compressed pulses had lengths at approximately 1 ps and peak powers of 20 kW, making such a system a serious competitor for bulk laser systems in several applications. Rusu and Okhotnikov [48] used a similar effect, but in reverse, using the hollow-core fiber to prechirp the pulses from a fiber mode-locked laser before coupling them into the Yb-doped gain fiber, in which they were recompressed nonlinearly. The result was spectral compression, resulting in a virtually transform-limited pulse train of 1.3 ps pulses with a peak power of 1.25 kW. In a similar spirit [49], 1.5 W, 47.5 MHz pulse train of 310 fs pulses was transformed into a 97 W train of almost transform-limited 10 ps pulses.

Although the nonlinear response of hollow-core fibers is far less than that of standard fibers, they do nonetheless have a nonlinear response that manifests at far higher optical powers. Ouzounov and colleagues [19] have shown that this enables high-power ultrashort optical pulses to be delivered as solitons through a hollow-core fiber, with minimal spectral or temporal degradation. Soliton energies reported were ~ 450 nJ at 1450 nm wavelength and, in a separate experiment [50], 60 nJ at 800 nm wavelength. Ouzounov *et al.* [51] have also demonstrated that at even higher powers (225 nJ, 100 fs pulse length), soliton compression in a short length of fiber was observable. The fiber was filled with Xe (4.5 bar) to suppress the Raman effect while enhancing the Kerr response. The observed compression was limited to a factor of 2, but based on their calculations they predict that, for example, a 1 ps

input pulse could be compressed down to 65 fs if a pulse energy of 210 nJ was used.

Soliton compression can be observed in solid-core PCFs too, and at previously unattainable wavelengths [52,53]. Of course, in solid-core fibers propagation of short pulses as solitons results in a strong self-frequency shift due to the Raman effect from the glass, and this has been used by several groups [54,55] to develop tunable all-fiber pulse sources.

8. RECENT AND FUTURE DEVELOPMENTS

Photonic crystal and microstructured fibers are having a profound impact on several aspects of fiber laser development, and new developments are rapid. At the same time as very high gains are allowing shorter gain fibers, new double-clad fiber designs [15,16] are offering significantly lower nonlinear response coupled with resistance to bend loss. One promising approach [16] is to use a small number of relatively large air holes to define the waveguide. The large holes help suppress bend loss while the fact that there are just a few of them causes a high differential modal attenuation, favoring the desired mode. In the field of cavity design, a tunable regeneratively mode-locked fiber laser with a 10 GHz repetition rate [56] used a short length of highly nonlinear PCF for intracavity pulse compression. Recently developed all-solid photonic bandgap fibers [18] have been used to provide simultaneous gain and anomalous dispersion in a passively mode-locked Yb fiber laser [57], although the material and higher-order dispersion will limit their ultimate performance. In a different application of these fibers, Wang and co-workers [58] showed that their strong spectral attenuation enabled them to be used as intracavity spectral filters. Incorporating them into the cavity provided a strong wavelength dependence of attenuation, enabling a Nd-doped fiber to lase on the three-level transition at 907 nm rather than the more common four-level transition at 1080 nm. Another way to perform spectral selection is through the use of Bragg gratings, and it has been shown [59] that in at least some cases useful gratings can be written in PCFs using standard 193 nm radiation. Fiber lasers continue to evolve at a rapid rate, both with and without PCF, and with new application areas opening up it is too early to predict what the most effective designs will eventually be. However, with the remarkable breadth of applications to lasers and laser sources already demonstrated, and with a range of new possibilities being investigated, the impact of PCF technology on fiber lasers is not going to go away.

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